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Moving integrated weed management from low level to a truly integrated and highly specific weed management system using advanced technologies

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Abstract

Integrated weed management (IWM) is one of the most commonly referred to approaches for sustainable and effective weed control in agriculture, yet it is not widely practiced, likely because current IWM systems fail to meet performance expectations of growers. The effectiveness and value of IWM systems should increase with increasing application specificity and true integration made possible with contemporary advances in technology, information systems and decision support. IWM systems can be classified based on their degree of application specificity and level of integration of tactics. In the application specificity pathway, a tactic is applied at a range of scales, from subfield to plant specific. In the integration pathway, multiple weed control tactics are combined in a synergistic manner. We hypothesize that the full value of IWM can and will be realized only when current and emerging technological innovations, information systems and decision tools are synergistically combined for use in real time. The True IWM system we envision requires automation and robotic technologies, coupled with information and decision support systems that are available or emerging but not yet enabled, in a proven integrated platform. Examples of low-level, traditional and precision IWM systems are discussed, and research needs for a True IWM system are presented. We conclude that the immediate call should be for a long-term investment in R&D and education (both theoretical and empirical) to develop and implement True IWM systems, an effort best accomplished in a public–private partnership where all essential entities are fully engaged and adequately resourced, including growers from all countries who will utilize IWM.

Keywords: IWM, precision agriculture, robotics, sensors, site-specific, weeds

Introduction

Integrated weed management (IWM) has long been proposed as a framework for the sustainable, effective management of weeds through the use of appropriate cultural, mechanical, biological and chemical weed control tactics (Ross & Lembi, 1985; Lewis *et al.*, 1997; Mortensen *et al.*, 2000). When used in a system approach that accounts for variation in abiotic and biotic conditions, IWM promises to minimize environmental and human health risks while maintaining profitability (Zoschke & Quadranti, 2002). While a range of IWM approaches are implemented today, none approaches the full potential of IWM, largely because they are limited in their application specificity and/or in their effective integration of available tactics.

Two important problems plague contemporary IWM: the range of possible integration scenarios considered as IWM is problematic (Harker & O'Donovan, 2013) and traditional or more advanced IWM is based on knowledge-intensive practices (Mortensen *et al.*, 2012). A low level of application specificity with limited or no integration of weed management tactics characterizes simple IWM systems. An IWM ensemble that includes only one tactic is considered low level, even if there is variation within the tactic, such as where chemicals are rotated or different cultivation methods used. In fact, Harker (2013) reported that the integration of multiple herbicides with various modes of action or application timings does not constitute an accepted form of IWM. Mortensen *et al.* (2012) identified that the limitation to adoption of traditional IWM is its basis in knowledge-intensive practices, not on saleable products. Therefore, much higher levels of integration of tactics and application specificity are needed to achieve success in IWM. We hypothesize that the full value of IWM can and will be realized when IWM systems incorporate current and emerging technological innovations, information systems and decision tools that increase application specificity and maximize integration of weed management tactics.

A key challenge in the management of agricultural cropping systems is to ensure that the increasing concerns about the environment and human health can be addressed in ways that are understandable, amenable and economically viable to the grower and the consumer. Integrated weed management approaches can be categorized by the level of application specificity and management tactic integration (Fig. 1). A single weed management tactic that is broadcast-applied over a range of conditions has limited application specificity and no integration, thus classifying it as low-level IWM at best, with almost none of the benefits of IWM. As the level of integration increases, knowledge of the ecology and biology of the managed cropping system also increases, along with the incorporation of greater numbers of tactics. These are traditional IWM systems (Fig. 1) focused on breaking weed reproduction cycles in the context of the cropping system. Without much application specificity, traditional IWM approaches have limitations relative to field scale. For example, under unfavorable soil and/or weather conditions, windows for field operations can be limited, thereby creating opportunities for weeds to proliferate, which when conditions for management later improve have much higher requirements for control. These higher management requirements must compete with other time-dependent activities, such as insect, disease, fertility and irrigation water management, that often compete for the same labor and equipment.

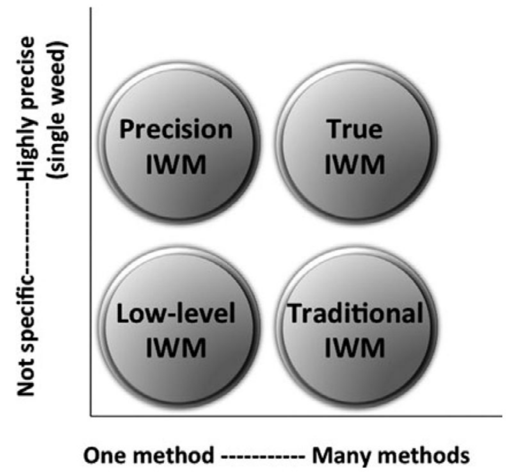

Figure 1. Integrated weed management (IWM) approaches based on weed target application specificity and level of integration

Application specificity can be increased through the use of precision agriculture that accounts for spatial and temporal variability of weed populations in a field (Christensen *et al.*, 2009). At low levels of integration, these systems are classified as precision IWM systems that, for example, utilize technology to identify weed patches and apply herbicides only to the patches where weeds are present. While application specificity is increased through the use of technology, without integration of weed management tactics, precision IWM systems cannot achieve the full value of True IWM (Fig. 1).

True IWM is achieved when both application specificity and integration are at high levels (Fig. 1). True IWM is technology-enhanced, information-based and decision-focused, such that the most appropriate weed control tactic can be identified from a suite of options that are available in the field at once, combining traditional and precision IWM into a total systems approach. True IWM is a plant level-specific approach that accounts for weed biology and the ecological conditions through space and time.

IWM examples

Low-level IWM

Single tactic approaches are encouraged for weed management because of the ease of application and availability and scale of equipment. Herbicide resistance is a widely and well-documented example of why single tactic approaches are low-level IWM (Van Gessel, 2001; Neuman & Pollack, 2010; Heap, 2013), yet they are not the only tactic that is commonly extensively relied upon. Cultivation is another example of an important and often overused tactic for weed control in cropping systems. Excessive and continuous use of cultivation can have destructive effects on the environment. An increase in soil erodibility is one of the most prominent common negative effects of cultivation. Herbicides and cultivation are just two examples of approaches to weed management that are low-level IWM. The lack of tactic integration and application specificity in low-level IWM may confer economic benefits, but the trade-offs include unintended consequences for humans or the environment.

Traditional IWM

The practice of using 'many little hammers' instead of one big hammer or single tactic is the approach for ecologically based and traditional IWM (Liebman & Gallandt, 1997; Westerman *et al.*, 2005). The many little hammers idea exploits knowledge of the biology and ecology of the plants (weed life cycles) to implement specific management approaches. For example, crop–weed competition, weed predation, weed seed decay and weed germination can all, if exploited appropriately, reduce the success of the weed. In current large- and medium-scale farming operations that employ traditional IWM, it is only possible to employ methods at discrete times over the course of a season, due to crop stage, field conditions or weather. Often, a delay in applying necessary tactics either results in poor weed control or necessitates a higher rate of an input. Without technology, traditional IWM is spatiotemporally limited in accounting for crop type and subsequent control actions.

Precision IWM

With the development of precision agriculture has come the idea of precision weed control, which can be map-based or in real time (Schueller, 1992). Precision IWM is primarily the targeted application of a tactic (e.g. herbicides) to a patch or group of weeds based on whether they are present or not. Using digital imagery, once vegetation is separated from the soil background, weeds are then distinguished from the crop using spectral, spatial and/or textural information (Thorp & Tian, 2004). For example, *Cynodon dactylon* (L.) Pers., the most troublesome weed in Louisiana sugarcane, was controlled with herbicides applied only to where the weed was present in the field. The selective application was through the use of the WeedSeeker® system that uses sensors to detect differences in spectral characteristics of light reflected from green plant material and bare soil (Griffin *et al.*, 2012). In another example, Van Evert *et al.* (2009) used texture to discriminate between broad-leaved *Rumex obtusifolius* L. (green) and grass (also green). Technology for precision IWM is largely underutilized, as the time and expense of modifying currently available equipment, a short-term solution, are favored over long-term system changes. For example, field design and crop layout may need to change dramatically to more fully incorporate automation and robotic platforms.

True IWM

Sensors, computer hardware, algorithms and robots are the core areas of advanced technology allowing for integration and application specificity of weed management tactics at the highest level. While still in the research phase, robotic platforms using light and durable materials are being developed for carrying out True IWM. Included on these platforms can be a combination of (i) sensors for capturing images and spectral reflectance of objects to discriminate between weeds and crop plants; (ii) computer hardware that can store large amounts of data and process it quickly for use in sophisticated algorithms that direct robotic operations independent of spatiotemporal constraints and (iii) detailed communication systems with cloud computing and access to global data for operating in concert and in real time. There is now a rich literature in the field of agricultural engineering and technology on automatic and robotic devices with sensors and hardware for weed control (see reviews by Thorp & Tian, 2004; Slaughter *et al.*, 2008a; Singh *et al.*, 2011). For example, Slaughter *et al.* (2008b) used visible and near-infrared reflectance spectroscopy to distinguish between types of lettuce varieties from weed foliage. A machine vision-based detection system by Nieuwenhuizen *et al.* (2010) was used in sugar beets to identify and control volunteer potatoes with almost 80% accuracy and very low crop death (1%).

Achieving True IWM

The goal of True IWM is to achieve the highest level of integration and application specificity of weed control tactics that minimize health and environmental risks while maintaining profitability. The roadmap to True IWM is not clear. What is clear is the disproportionality of efforts between traditional herbicide-based weed management systems and IWM of any level. If conceptually achievable, what then would it take to fully implement a True IWM system? The answer is found in three fundamental missing pieces–funding (very limited), institutional support (lacking in both public and private sectors) and a systems focus in research, development and implementation of True IWM (missing from many research programs). The reality for chemical weed control is a massive investment in money and time that largely comes from crop protection chemical companies, but is also supported by private and public institutions. McDougall (2016) estimated that for a new crop protection product in the period 2010–2014 for five major companies, the costs were $286 million, corresponding to 37% for research, 51% for development and 12% for registration, requiring 11 years of effort. In 2014, the total R&D budget for 11 major companies to develop new crop protection products was $2.6 billion of which 93% was allocated to chemical weed control and the remaining 7% to biocontrol products. Additionally, the magnitude of the resources spent each year on herbicide evaluation by public and private entities is considerable. To our knowledge, there is no comparable R&D program supporting research, development and implementation of True IWM systems or the education/outreach programs required to achieve success. The immediate call should be for a long-term investment in R&D and education (both theoretical and empirical), best accomplished in a public–private partnership where all essential entities are fully engaged and adequately resourced, including growers who will utilize True IWM.

Using our operating hypothesis that the viability and utility of IWM can be realized in the very near future with full utilization of current and emerging technological innovations, information systems and decision tools, we have identified the following research areas to increase application specificity and maximize integration of weed management tactics:

- Microrates of inputs (e.g. herbicides, cultivation, heat) that control weeds
- Optimal growth stages of weeds for highest microrate efficacy
- Ecological interactions of weeds and response to the environment
- Occlusion of plant parts for accurate and reliable identification
- Pre-germination identification of weed seed in the soil
- Incorporation of historical field data for preventative IWM strategies
- Robotic platforms that withstand weather conditions and continuous use
- Data processing in real time to increase travel speed in the field
- Fast actuators to effectively and efficiently damage or kill weeds
- Articulating robotic machinery with agility for precision applications

A systems research approach is needed that accounts for each of these areas and brings together different disciplines, including weed biology, agronomy, computer science, engineering and socioeconomics. The human dimensions of True IWM systems cannot be underestimated or overlooked. Along with research on the technical details of implementing True IWM, there are equally important questions related to its adoption. Will growers have difficulty operating the equipment used for True IWM? How much will it cost to acquire equipment for True IWM? Will the savings on reduced inputs using True IWM outweigh the costs? Can savings associated with less environmental degradation and reduced human exposure to chemicals be accounted for with True IWM? Working with growers and farm organizations and their advisors, both public and private, will be essential in designing and implementing useful True IWM systems.

True IWM is a concept as much as it is a practice. The poorly resourced farmers in developing countries who often use low-tech approaches to control weeds (e.g. hand weeding) have high specificity, but low system integration (Figure 1) just like in developed countries where only cultivation or herbicides are used (low-level IWM). Weed management problems are significant in developing countries (Gianessi, 2009), yet True IWM is still applicable albeit with a different tool set than that used in crop production systems in developed countries. Further, the same lack of research, education and outreach applies to developing countries suggesting a major effort in implementing True IWM for the broad range of agricultural production systems globally.

True IWM is not a "silver bullet" but rather an approach that allows growers to move away from low level and maximize traditional or precision IWM approaches for weed control in cropping systems. True IWM is revolutionary because all weed control tactics are put on a level playing field, none is relied upon more than another, and computerized decision-making decides the right tool at the right place for a particular weed. With advanced technology, integration and application specificity of tactics are maximized in a True IWM approach, while the limitations of space and time are reduced significantly.

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